SPHERICALLY-ENCLOSED FOLDED IMAGING SYSTEM

BACKGROUND

[0001] Movable sensor turrets have been developed that provide the ability to direct imaging systems and illumination systems contained within a turret housing in a desired direction. In certain applications, such as those for use on aircraft and other moving platforms, sensor turrets may include a moveable spherical housing or sensor "ball" for improved aerodynamics. The spherical housing or ball is often part of a gimbal or pivot assembly and may be able to rotate on one or more axes. In certain applications, a sensor turret or sensor ball may contain stabilization features such as gyroscopes and actuators for improved imaging.

[0002] Because of the limited space available within a given sensor turret or sensor ball, the included imaging systems have previously been limited in size, e.g., the primary mirror size for a given focal length, and/or field quality. Furthermore, the presence of one imaging or illumination system within a sensor ball has typically precluded the simultaneous use of different systems for other illumination and imaging purposes.

[0003] What is needed therefore are systems and methods for obtaining compact, high field-quality spherically-enclosed imaging systems for use within a sensor ball of a given size. What is further needed are systems and methods for obtaining spherically-enclosed imaging systems that have relatively wide fields of view (FOV).

SUMMARY

[0004] Embodiments of the present invention are directed to systems and methods for obtaining compact, high field-quality folded imaging systems for use within a sensor ball of a given size. The spherically-enclosed folded imaging systems may be diffraction-limited and may have relatively wide fields of view (FOV).

[0005] A first embodiment of the present invention may include an imaging system adapted to fit within a spherical housing. The imaging system may include a primary mirror that has a diameter that is smaller than an interior diameter of the spherical housing. The imaging system may also include a secondary mirror configured to receive light reflected from the primary mirror. A first fold mirror may be configured to receive light from the secondary mirror and a second fold mirror may be configured to receive light from the first fold mirror. Light from the second fold mirror is directed to a focal plane within the spherical housing and a field of view (FOV) may be imaged within the spherical housing.

[0006] The primary and secondary mirrors may each be elliptical, parabolic, hyperbolic or spherical. The imaging system may include one or more beamsplitters to produce two or more optical channels within the spherical housing. The imaging system may include a field corrector for each optical channel. A detector may be included for one or more of the optical channels and the detectors may include a focal plane array (FPA). The second fold mirror may be transparent to a desired infrared wavelength and the imaging system may include a medium wave infrared (MWIR) or long wave infrared (LWIR) camera having a FPA, a dewar, and a cold stop. The imaging system may include a cube beamsplitter that may have correction structures. The system may be diffraction-limited. In certain embodiments, the imaging system may have an f-number between about f/3 to about f/8. The imaging system may include a cold shield operable to image a FPA onto a cold stop. The cold shield may include a centrally transmissive region. The imaging system may also include a wide field of view WFOV acquisition camera placed in a central obscuration of the secondary mirror within the spherical housing.

[0007] A second embodiment may include an illumination and detection system adapted to fit within a sphere. The illumination and detection system may include a spherically-enclosed folded imaging system having primary and secondary mirrors and two or more fold mirrors. The illumination and detection system may also include a first laser illumination system. The first laser illumination system may be operable to produce an output with a first range of wavelengths. The first range of wavelengths may be centered at about 1 micron. The first range of wavelengths may be centered at about 1.5 microns. The spherically-enclosed folded imaging system may include a MWIR or LWIR channel.

[0008] A third embodiment may include a method of constructing a spherically-enclosed folded imaging system having a wide diffraction-limited field of view. Hyperbolic primary and secondary mirrors may be placed inside a spherical housing. Two or more fold mirrors may be placed inside the spherical housing. A beamsplitter may be placed in the spherical housing to receive an input from a last fold mirror of the two or more fold mirrors. Two or more field correctors may be placed in the spherical housing. A detector or a camera may be placed in the spherical housing to receive an image from one of the two or more field correctors. The step of placing a beamsplitter in the spherical housing may include placing a cube beamsplitter having correction structures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings. The drawings include the following:

[0010] FIG. 1 shows a simplified design for a spherically-enclosed folded imaging system.

[0011] FIG. 2 shows a side view of a dual-channel spherically-enclosed folded imaging system.

[0012] FIG. 3 shows an alternate dual-channel spherically-enclosed folded imaging system.

[0013] FIGs. 4A-4C show three-channel spherically-enclosed folded imaging systems.

[0014] FIG. 5 is a perspective view of the imaging system of FIGs. 4B and 4C.

[0015] FIG. 6 includes FIG. 6A and FIG. 6B, which show front view and side views respectively of an alternate three-channel spherically-enclosed folded imaging system.

[0016] FIG. 7 shows a cold shield for use in certain embodiments having one or more infrared channels.

[0017] FIG. 8 shows an alternate design of a cold shield.

[0018] FIG. 9 shows steps in a method of manufacturing a spherically-enclosed folded-imaging system.

DETAILED DESCRIPTION

[0019] The present invention may be understood by the following detailed description, which should be read in conjunction with the attached drawings. The following detailed description of certain embodiments is by way of example only and is not meant to limit the scope of the present invention.

[0020] Embodiments of the present invention are directed to telescopes or imaging systems that are enclosed in a movable housing of a sensor turret or sensor ball. The imaging systems may be compact, high beam-quality folded imaging systems for use within a sensor ball of a given size. The spherically-enclosed folded imaging systems may have high field-quality, may be diffraction-limited and may have relatively wide fields of view (FOV). The housing may be part of a gimbal assembly and may be adapted for applications where aerodynamic considerations are important. In certain applications, the housings may be spherical or in certain embodiments it may be aspherical, e.g., an ellipsoid, oblate or prolate spheroid, etc. Embodiments may also include illumination systems.

[0021] FIG. 1 shows a design for a spherically-enclosed folded telescope or folded imaging system **100**. The imaging system **100** may be enclosed in a spherical housing **2** having a transparent window **4**. A concave primary mirror **102** and a convex secondary mirror **104** are arranged within the spherical housing **2** to receive light entering the window **4** and to focus the light at a focal plane **110**. It will be understood that for the configuration shown, the convex surface of the secondary mirror is facing the primary mirror **102** and the concave surface of the

primary mirror is facing the secondary mirror **104**.

[0022] First and second fold mirrors **106** and **108** are present to move the optical path off the path between the primary and secondary mirrors and to the focal plane **110**. A field corrector **112** and/or a beamsplitter (not shown) may be present in the optical path between the second fold mirror **108** and the focal plane **110**. When a beamsplitter is present, two or more optical channels may be created and utilized. By having one or more fold mirrors, the imaging system **100** and the optical path may be folded within a given volume to produce a short, compact, large-aperture, wide field of view imaging system.

[0023] A detector (not shown), for example, a focal plane array (FPA), may be placed at the focal plane **110** to allow viewing or recording of an image in the field of view (FOV) of the imaging system **100**. A telescope tube or baffle **114** may be present to reduce stray light from entering the imaging system **100**. The baffle **114** may be perforated to allow laser or sensor beams to cross. Light entering the window is depicted by ray traces **116** as shown.

[0024] Light entering the window **4** travels within the spherical housing **2** and the baffle **114** (when present) to the primary mirror **102**. From the primary mirror **102**, the light is reflected to the secondary mirror **104**. From the secondary mirror **104**, the light is reflected back toward the primary mirror **102** and travels within the cone or cylinder of obscuration produced by the secondary mirror **104**. The light is then reflected by the first fold mirror **106** and travels to the second fold mirror **108**. At the second fold mirror **108**, the light is redirected to the field corrector **112**, when present, and the focal plane **110**.

[0025] The first and second mirrors **102** and **104** may be characterized by different conic constants. For example, in certain embodiments, the primary mirror **102** may be parabolic and the secondary mirror **104** may be hyperbolic, producing a Cassegrain design. In other embodiments, the primary mirror may be elliptical and the secondary may be hemispherical or vice versa, resulting in a Dall-Kirkham design and a Pressman-Carmichael design, respectively. In still other embodiments, the primary and secondary mirror may both be hyperbolic, producing a Ritchey-Chretien design.

[0026] In certain applications, portions of the volume of a spherical housing of sensor turret or ball may be occupied by various objects and equipment, e.g., structural members, illuminations systems, etc., in addition to an imaging system, e.g., system **100**. Accordingly in certain embodiments, an imaging system according to the present invention may be designed to fit within a reduced volume, e.g., a hemisphere, of a given sensor ball.

[0027] FIG. 2 shows a side view of a side view of a dual-channel imaging system **200** adapted for enclosure in a hemisphere of a spherical housing of a turret or sensor ball. A concave primary mirror **202** is shown in relation to a convex secondary mirror **204**. The primary mirror **202** and the secondary mirror **204** may be optically aligned, as shown, to receive light from a transparent window in a housing of the ball. Ray traces **218** are shown for rays entering the entrance aperture or window of the surrounding ball (not shown) and passing an obscuration presented by the secondary mirror **204**. This embodiment may be useful when internal structure of the ball, e.g., bar **6**, limits the space available within the ball. The optical axis may be folded within the spherical housing **2** as desired by inclusion of a number of fold mirrors having the appropriate orientation.

[0028] A first fold mirror **206** folds or redirects the optical path from the secondary mirror **204**, e.g., as shown off of a diameter **8** of the ball. A second fold mirror **208** redirects the optical path to a third fold mirror **210**, where the optical path is directed to a beamsplitter **212**. In certain embodiments, the beamsplitter **212** may be a polarizing beam splitter. In certain embodiments, the beamsplitter **212** may be a cube beamsplitter made of optical glass, type BK7.

[0029] The beamsplitter **212** may have correction structures formed on the input surface and outputs surfaces to facilitate the reduction of aberrations such as spherical aberration, astigmatism, field curvature and coma. The correction structures may be spherical or aspheric, e.g., ellipsoidal, parabolic, hyperbolic. For example, a convex hemispherical correction structure **212b** may be formed on the input face of the beamsplitter **212** and a convex hemispherical correction structure **212c** may be formed, e.g., ground, into each of the output faces of the beamsplitter **212**.

[0030] The beamsplitter **212** divides the incident light into two output channels (with only one output channel shown for clarity). A field flattener or corrector **214** may be present to improve characteristics of the focal plane, e.g., by reducing field curvature introduced by the primary and secondary mirrors **202** and **204**. In certain embodiments, the primary mirror may have a hole or depression to accommodate the placement of the first fold mirror, in which case the mirror may be referred to as a "holey" mirror.

[0031] Additional systems such as a separate wide field of view acquisition (WFOV) cameras and/or laser illumination systems **216** may be placed within the ball housing in front of the obscuration created by the secondary mirror **204**. Such additional systems may be limited in certain embodiments to an overall diameter equal to that of the secondary mirror and/or central obscuration.

[0032] The components of the imaging system **200**, including the primary and secondary mirrors **202** and **204**, may be designed and configured to fit within a sensor ball of a given diameter. For example, for the configuration shown in FIG. 2, an embodiment with a 14" hyperbolic primary mirror and a 6" hyperbolic secondary mirror was designed for enclosure within a sensor ball spherical housing with inner diameter of 20 inches. Diffraction-limited results were verified with commercial optical modeling software within a field of view (FOV) of plus or minus 0.3 degrees, for a total diffraction-limited FOV of 0.6 degrees. The throughput of the imaging system was determined to be 78%. The software used was ZEMAX software. ZEMAX is a registered trademark for software for optical design by ZEMAX Development Corporation.

[0033] FIG. 3 shows a spherically-enclosed folded imaging system **300** in which a second fold mirror **308** is placed ahead of an obstructing internal support bar **6** of a surrounding spherical housing **2**. A concave primary mirror **302** and a convex secondary mirror **304** are aligned as shown. A first fold mirror **306** is positioned to redirect the optical axis away from the primary mirror **302** to the second fold mirror **308**. Ray traces **316** are show for light that has entered the spherical housing **2** through a window (not shown).

[0034] The second fold mirror **308** may be placed ahead of a centrally occupied area or region of the spherical housing **2** or ball, as shown. This position of the secondary fold mirror **308** may be advantageous in certain sensor ball applications where a support bar **6** is present in the interior of the spherical housing **2**.

[0035] A beamsplitter **310** may be present to create two optical channels (one channel is omitted from the drawing for clarity). The beamsplitter **310** receives light from the second fold mirror **308**. The beamsplitter **310** may be a cube beamsplitter with a mirrored surface **310a**, an input surface **310b**, and two output surfaces **310c**. The input surface **310b** and output surfaces **310c** may have correction structures, similar to the embodiment of FIG. 2. For each optical channel leaving the beamsplitter, a beam corrector **312** may be present. Each of the optical channels may be received by a desired device or element, e.g., a focal plane array (FPA) **314**, a camera, etc.

[0036] For the configuration shown in FIG. 3, slower optical systems with higher f-numbers (f/#) may be achieved for a given primary mirror size. The configuration shown may additionally facilitate the use of a primary mirror **302** that approaches the inner diameter of the enclosing spherical housing **2** while still allowing for the placement of one or more additional illumination or imaging systems within the central obscuration of the folded imaging system **300**.

[0037] FIG. 4A shows a three-channel spherically-enclosed folded imaging system **400** including three optical channels, e.g., two near infrared channels (NIR) and a medium-wave infrared (MWIR) channel. A concave primary mirror **402** is aligned with a convex secondary mirror **404**. A first fold mirror **406** directs light reflected from the secondary mirror **404** to a second fold mirror **408**. The primary mirror **402** and the first fold mirror **406** are shown as "holey" mirrors, i.e., each mirror has a central hole through which light can pass. The central holes may be formed with a desired orientation to allow the optical path of the imaging system **400** to pass through the mirror in a desired direction. In certain embodiments, the first fold mirror **406** may be positioned within a hole or depression in the primary mirror **402**. Ray traces **426** are shown for light that has entered the spherical housing **2** through a transparent window

(not shown).

[0038] The first fold mirror **406** receives light from the secondary mirror and is tilted to reflect the light to a second fold mirror **408**. The second fold mirror **408** is configured to receive the light from the first fold mirror **406** at an incidence angle of zero degrees. Because of the zero-degree incidence angle, the second fold mirror **408** reflects the light back in the direction of the first fold mirror **406**. Due to the focusing effect of the primary and secondary mirrors **402** and **404**, the light returning to the primary fold mirror occupies a smaller area and as a result is able to pass through the hole in the primary fold mirror.

[0039] The second fold mirror **408** directs light through the first fold mirror **406** and primary mirror **402** to a beamsplitter **410** that splits the incoming light into two output channels (one channel is omitted for clarity). A field corrector **412** may be used with each output channel of the beamsplitter to improve field characteristics at a detector **413**, which may be a focal plane array (FPA).

[0040] The field corrector **412** may include one or more refractive elements to correct field curvature, astigmatism, and/or coma. The detector may be of any suitable material appropriate for detection of the particular optical channel. For example, in certain embodiments, detector materials may include indium antimonide (InSb) for detection of wavelengths from 1-5 microns. Also, mercury cadmium telluride (HgCdTe) may for example be used in certain application for wavelength ranges from 0.85-2.5 microns in FPAs, e.g., the HAWAII 2 FPA from Rockwell Scientific Company.

[0041] The second fold mirror **408** may be transparent to a desired infrared range, e.g., a medium-wave infrared (MWIR) range of 3-5 microns or a long-wave infrared (LWIR) range of 9-12 microns, and a corresponding infrared (IR) channel may accordingly be extracted from for infrared imaging at a focal plane array **416** of suitable infrared detectors. In certain embodiments, the second fold mirror may be made of germanium or a germanium material, e.g., germanium oxide (GeO), zinc germanium (ZnGe), etc. One of skill in the art will recognize that other suitable infrared transparent materials may be used for the second fold mirror **408**.

[0042] One or more IR, e.g., MWIR, fold mirrors, e.g., mirrors **414** and **416**, may direct the IR light extracted from the second fold mirror **408** to a IR camera, e.g., a MWIR camera **418**. The MWIR camera **418** may include relay optics such as one or more lens pairs **420** and a MWIR detector or focal plane array (MWIR FPA) **422**. A dewar **424** may be present in certain embodiments to cool the MWIR FPA **422** for improved detection and imaging at desired wavelengths. A field corrector may optionally be used for the MWIR channel. In certain embodiments, a LWIR optical relay chain including a LWIR FPA and LWIR fold mirrors may be used.

[0043] For the configuration shown in FIG. 4A, an embodiment having a Ritchey-Chretien design with a hyperbolic 14" primary mirror **402** and hyperbolic 6" secondary mirror **404** was verified with commercial optical modeling software as having a diffraction-limited field over a FOV of plus or minus 0.4 degrees, for a total of 0.8 degrees diffraction-limited FOV. The throughput for this embodiment was determined to be 80%. The software used was ZEMAX software for optical design by ZEMAX Development Corporation.

[0044] FIG. 4B is a front view and FIG. 4C is a corresponding side view of an embodiment **400**, similar to the embodiment shown in FIG. 4A, with a primary mirror **402** of different size and a slightly different position of the secondary mirror **404** relative to a surrounding spherical housing **2**. The MWIR or LWIR channel is omitted for the sake of clarity. A central bar **6** is shown that may be part of the structural support of the spherical housing **2**. Ray traces **426** are shown for light that has entered the spherical housing **2**.

[0045] For the configuration shown in FIGs. 4B and 4C, an embodiment having a Ritchey-Chretien design with a hyperbolic 11" primary mirror **402** and hyperbolic 6" secondary mirror **404** was verified with ZEMAX commercial optical modeling software as having a diffraction-limited field over plus or minus 0.4 degrees, for a total of 0.8 degrees diffraction-limited FOV. The embodiment was designed to fit within a 20" diameter MX-20 sensor turret, or multi-sensor payload, produced by L3 WESCAM of Burlington, Ontario, Canada. The size of the diffraction-limited field of view represents an improvement over previous imaging systems having a

comparable overall system depth.

[0046] FIG. 5 is a perspective view of the imaging system of FIG. 4B and 4C. A hemisphere of a spherical housing **2** is shown which surrounds the primary mirror **402** and the secondary mirror **404**. In certain embodiments, the primary and secondary mirrors may be centered on a radius of the spherical housing **2**, for example as shown. In alternate embodiments, the primary and secondary mirrors **402** and **404** may be located at other locations within a spherical housing **2**, e.g., along a chord. A central obscuration **404a** created by the secondary mirror **404** is shown.

[0047] As described for FIG. 4A, the first fold mirror **406** receives light from the secondary mirror and is tilted to reflect the light to a second fold mirror **408**. The second fold mirror **408** is configured to receive the light from the first fold mirror **406** at an incidence angle of zero degrees. Because of the zero-degree incidence angle, the second fold mirror **408** reflects the light back in the direction of the first fold mirror **406**.

[0048] Due to the focusing effect of the primary and secondary mirrors **402** and **404**, the light returning to the primary fold mirror **406** occupies a smaller area and as a result is able to pass through the holes in the first fold mirror and primary mirror. The light passing through the first fold mirror **406** from the second fold mirror **408** is then received by the beamsplitter **410**. The beamsplitter **410** then directs the light to the field corrector **412**.

[0049] TABLE 1 shows the optical prescription data for the construction and/or optical modeling of one embodiment according to FIGs. 4B and 4C. The surface number that light would encounter sequentially after being admitted to a ball through a transparent window, e.g., window **4** in FIG. 1, is indicated in Col. 1. The radius of curvature of each surface is given in Col. 2, in units of inches. Col. 3 indicates the distance between successive surfaces, in units of inches. Col. 4 indicates the type of material for a particular optical element in the optical prescription. Col. 5 indicates the diameter of a particular optical element. The conic or aspherization constant for each optical element is given in Col. 6. Further comments for particular points in the optical path are indicated in Col. 7, with corresponding explanations, e.g., “coordinate break” indicating a direction change, are provided in the Footnotes at the bottom of

Table 1.

[0050] TABLE 1

14" Ritchey-Chretien Design for a 20" Ball						
Surface Col. 1 (#)	Curvature Col. 2 (inches)	Thickness Col. 3 (inches)	Glass Col. 4 (type)	Diameter Col. 5 (inches)	Conic Col. 6 (constant)	Comments Col. 7 (see footnote)
0	Infinity	Infinity			0.00	FN1
1	Infinity	10.4284		14.11768	0.00	FN2
2	-11.000	-2.00		14.00723	0.00	FN3
3	-26.68463	-7.79	Mirror	14.01283	-1.06832	FN4
4	-14.54667	7.040265	Mirror	6.054605	-2.994555	
5	-	0.00	-	-	-	FN5
6	Infinity	0.00	Mirror	5.04547	0.00	
7	-	-12.41821		-	-	FN6
8	-	0.00		-	-	FN7
9	Infinity	0.00	Mirror	1.673698	0.00	
10	-	1.261032		-	-	FN8
11	2.50706	1.234671	BK7	1.372982	0.00	
12	1.234745	1.231172		0.9567053	0.00	
13	0.6507285	0.06173355	BK7	0.8400265	0.00	
14	0.7478314	0.2481511		0.8216853	0.00	
15				0.7899602	0.00	FN9

Footnotes

FN1: Object-Entrance Pupil Diameter = 13.998 inches

FN2: Circular Obscuration, Maximum Radius = 7 inches

FN3: Circular Aperture, Maximum Radius = 14 inches

FN4: System Stop

FN5: Coordinate Break

FN6: Coordinate Break

FN7: Coordinate Break

FN8: Coordinate Break

FN9: Image

[0051] FIG. 6 includes a front view, FIG. 6A, and a side view, FIG. 6B, of an alternate design for a spherically-enclosed three-channel folded imaging system **600**. The three optical channels may be for example two near infrared channels (NIR) and a medium-wave infrared (MWIR) channel. A concave primary mirror **602** is aligned with a convex secondary mirror **604**. A first fold mirror **606** directs light reflected from the secondary mirror to a second fold mirror **608**. A surrounding spherical housing **2** is shown with a support bar **6**. Ray traces **616** are shown for light that has entered the spherical housing **2** through a window (not shown).

[0052] The second fold mirror **608** directs light to a beam splitter **610** that splits the incoming light into two output channels (one channel is omitted for clarity). A field corrector **612** may be used with each output channel of the beamsplitter to improve beam characteristics at a detector (not shown). The field corrector **612** may include one or more refractive elements to correct field curvature, astigmatism, and/or coma.

[0053] The second fold mirror **608** may be transparent to a desired optical range, e.g., a MWIR range of 3-5 microns, a LWIR range of 9-12 microns, etc. A third optical channel may be accordingly extracted from the second fold mirror **608**.

[0054] A wide field of view acquisition and illumination (WFOV) system **614** may be included within the ball **2** in the central obscuration of the secondary mirror **604** as shown in FIG. 6B. In certain embodiments, the WFOV system **614** may have a zoom lens capability with a variable field of view from 4 to 20 degrees. The WFOV system **614** may have target acquisition and/or laser illumination capability in the visible and infrared ranges. For example, the WFOV system **614** may include a laser operating at 1 micron and/or 1.5 micron for target illumination and designation.

[0055] For the configuration shown in FIGs. 6A and 6B, an embodiment having a Ritchey-Chretien mirror design with a hyperbolic 14" primary mirror **402** and hyperbolic 6" secondary

mirror **404** for use in a 20" ball was verified with ZEMAX commercial optical modeling software as having a diffraction-limited field over a FOV of plus or minus 0.4 degrees, for a total of 0.8 degrees diffraction-limited FOV. The f-number of the embodiment was f/4 and the throughput was 80%. The Airy disk was determined to be 6.4 microns in diameter.

[0056] FIG. 7. shows a cold shield **700** used as part of a spherically-enclosed folded imaging system, for example imaging system **400** in FIG. 4A, that has an MWIR channel and a dewar-cooled FPA **710**. A dewar may be included and is indicated by dewar window **704**. An MWIR optical element **702** with relay surface **702a** may be present in the MWIR optical relay chain outside of the dewar **704**. The MWIR optical element **702** and relay surface **702a** may be designed to image the MWIR FPA **710** onto a cold stop **706** inside of the dewar **704**. The relay surface **702a** may include a coating **702b** that is reflective to MWIR wavelengths. In certain embodiments, the cold shield **700** may be for a LWIR channel and may have corresponding LWIR optical elements.

[0057] A cold filter **708** may be present within the dewar **704** to facilitate attenuation of wavelengths outside of the MWIR or LWIR range of interest. Suitable cold filter materials may be selected as desired. In certain embodiments, the MWIR or LWIR optical element may be part of a filter wheel.

[0058] Ray traces for an image of the focal plane **710** are shown reimaged onto the cold stop **706**. A warm emitter **1** is shown, with ray traces from the warm emitter **1** being reflected from the optical relay surface **702a** and away from the dewar window **704**. The cold shield **700** may reduce stray MWIR or LWIR light, including thermally-emitted IR-wavelength photons from the "warm" elements of the MWIR or LWIR optical relay chain, from being received by the MWIR or LWIR FPA **710**. The cold shield **700** may accordingly allow attenuators and filters outside of the dewar **704** to act as "cold" elements, even though they are not actually inside the dewar **704**.

[0059] In certain embodiments, the coating **702b** may be on an element of the MWIR or LWIR optical relay chain immediately exterior to the dewar window **704**, with no intervening optical elements between the dewar window **704** and the coating **702b**. One of skill in the art will

understand that the coating **702b** may be placed on other optical elements in the MWIR optical relay chain.

[0060] FIG. 8 shows an alternate embodiment of cold shield **800** with ray traces shown originating from a MWIR focal plane array (FPA) **810** inside of a dewar **804**. An MWIR element **802** in the MWIR optical relay chain may have a coating **802b** on a relay surface **802a**. The relay surface may **802a** may be adjacent to the dewar **804**, indicated by dewar window **804**. The coating **802b** may be designed to act as an attenuator or passband filter. The MWIR element **802** may in certain embodiments be part of a filter wheel. The focal point of the coated relay surface **802a** is designed to be located at the position of a cold stop **806** within the dewar **804** so that the image of the MWIR FPA **810** is reimaged or focused onto the cold stop **806**. In certain embodiments, the cold shield **800** may be for a LWIR channel and may have corresponding LWIR optical elements.

[0061] A central portion of the relay surface **802a** may be coated to transmit MWIR wavelengths and may act as a central transmissive portion **802c**. Alternatively, a central transmissive region **802c** may be constructed by removing or deleting a central portion of coating **802b** from the element surface **802a**. Stray light from the MWIR image of the central obscuration of the secondary mirror, e.g., secondary mirror **404**, may be blocked or filtered by the inclusion of the central transmissive region **802c**. The central transmissive region **802c** may accordingly modify the effective diameter of the cold stop **806** of a MWIR camera. For example, a cold stop of an existing camera can be modified, e.g., changing a F/2.6 stop to a F/8 stop.

[0062] FIG. 9 shows steps in a method **900** of constructing a spherically-enclosed folded imaging system. Primary and secondary mirrors may be placed **902** inside a spherical housing. The primary and secondary mirror may have any conic constant. Two or more fold mirrors may also be placed **904** inside the spherical housing and may be configured to direct light from the secondary mirror away from the primary mirror. A beamsplitter, optionally having correction structures, may be placed **906** in the spherical housing and may be configured to receive an input from a last fold mirror of the two or more fold mirrors. A field corrector may be placed **908**

within the spherical housing to receive an output channel from the beamsplitter. A detector or camera may also be placed **910** in the spherical housing to receive an image from a field corrector. In certain embodiments, the step of placing a camera in the spherical housing may further include the step of placing an MWIR camera with a dewar in the spherical housing. An imaging system constructed by the above method **900** may be diffraction-limited and may have a wide field of view for one or more optical channels. The one or more channels may be in the UV, visible, NIR, MWIR and LWIR wavelength ranges.

[0063] Operation of a folded imaging system will now be described with reference to the drawings. An imaging system, e.g., imaging system **400**, may be placed within a spherical housing of a sensor turret or sensor ball as a compact, high magnification imaging system. A wide field of view (WFOV)acquisition imaging system or camera may be placed within the central obscuration created by the secondary mirror of the imaging system. The acquisition system may act as a spotting system and the imaging system may act to magnify the FOV once a desired target or object is located with the WFOV system. In certain embodiments, the WFOV acquisition imaging system may have a WFOV of about 4 to 20 degrees.

[0064] Once a target or object of interest is acquired within the FOV of the imaging system **400**, it may be viewed or recorded. The object may be viewed in real time, image signals may be recorded for post processing, and pictures may be taken on each of the one or more optical channels.

[0065] In certain embodiments, a laser illumination system may be included within the spherical housing illuminate a target. The target may be imaged with a spherically-enclosed folded imaging system, e.g., system **600** of FIG. 6. In certain embodiments, a laser designation system may be included within the spherical housing to designate the target by illumination at a specified wavelength, e.g. 1.5 microns.

[0066] Thus, by having fold mirrors the present invention may provide short, compact, large-aperture, wide field of view telescopes or imaging systems within the confines of an enclosing

spherical housing of a turret or sensor ball. Two or more optical channels may be created with the use of a beamsplitter.

[0067] A beamsplitter may be used to provide improved field and aberration corrections. The beamsplitter may be a cube beamsplitter. By optionally included field correction structures, such a beamsplitter may further improve beam quality and may facilitate diffraction-limited field characteristics. The ability to have a short, compact imaging system with a low f-number (f/#) increases the magnification ability and brightness of the imaging system.

[0068] Embodiments may be diffraction limited, including certain embodiments having Ritchey-Chretien mirror designs. For example, the embodiments described above for FIGs. 2-7 have been validated as diffraction limited by commercial optical modeling software when the primary and secondary mirrors are designed as hyperbolic. The software used was ZEMAX software for optical design by ZEMAX Development Corporation.

[0069] Cold shields as described above may allow "commercial-off-the-shelf" (COTS) MWIR cameras to be improved or modified for use in spherically-enclosed folded imaging system. By inclusion of a filter wheel, a cold shield may provide remote change capability of MWIR optical channel characteristics, e.g., cold stop size, bandpass characteristics, etc.

[0070] Although the present invention has been described in detail with reference to certain preferred version thereof, other versions are possible. For example, while use of hyperbolic primary and secondary mirrors in Ritchey-Chretien designs have been described above in certain detail, the primary and secondary mirrors may have other shapes, e.g., parabolic, elliptical, and hemispherical. Accordingly, the present invention includes embodiments that have Dall-Kirkham design, Press-Carmichael design, and Cassegrain designs. Such embodiments may be diffraction-limited with the inclusion of image processing means, e.g., an image processor and/or computer running a MATLAB or Interactive Data Language (IDL) deconvolution routine or other deconvolution routines, e.g., Lucy-Richardson based deconvolution routines, to remove coma and/or other aberrations.

[0071] Additionally, while embodiments described above have included a single medium wave infrared (MWIR) or long wave infrared (LWIR) channel, one or more beamsplitters may be used to produce multiple MWIR and/or LWIR channels. Furthermore, where embodiments described above have included description of MWIR channels, long infrared channels may be used with appropriate material selection of the IR relay chain and detector elements.

[0072] One of skill in the art will understand that any suitable detector or focal plane array may be used within the scope of the present invention. Focal planes may be of any desired size to capture the FOV at the focal plane. Any of various detector materials suitable for desired wavelength ranges may be used. Charged-coupled devices (CCDs) may be used in focal plane arrays in certain embodiments.

[0073] One of skill in the art will also understand that while the description above is generally directed to imaging of NIR, MWIR, and LWIR light, the scope of the present invention also includes imaging of visible light, e.g., in the 400 to 700 nanometer wavelength range, and ultraviolet (UV) light.

[0074] The reader's attention is directed to all papers and documents that are filed concurrently with this specification and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference. All the features disclosed in this specification, including any accompanying claims, abstract, and drawings, may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise.